LaserNetUS – Research Opportunities in IFE

<u>**LaserNetUS Facilities and Points of Contact**</u>

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<u>*IFE White paper topic*</u>
Holistic support for IFE including target physics and designs, targets, materials, diagnostics, driver technology, simulations, and workforce.

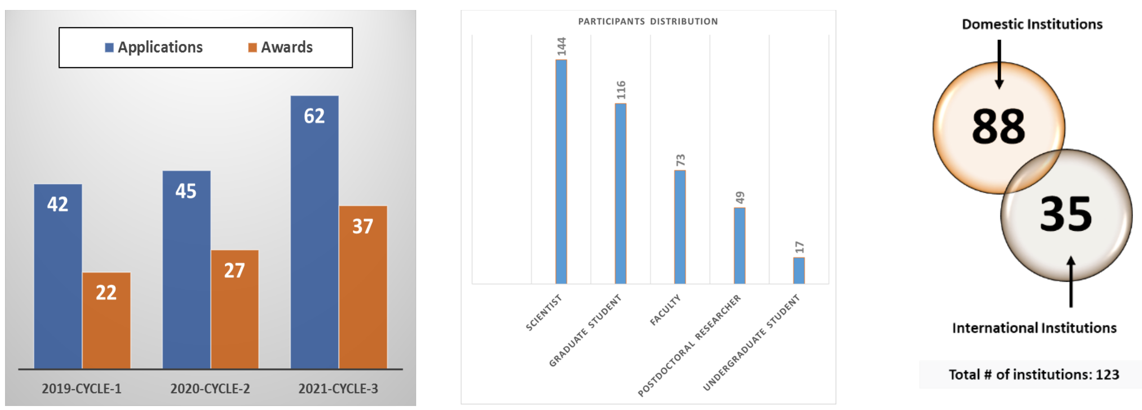
Executive Summary

LaserNetUS is a network of high-power laser facilities supported by the Department of Energy Office of Fusion Energy Sciences and operating effectively as a user facility. Its mission is to provide the brightest light for its users at no cost, to advance the frontiers of laser-science research, to develop better technology for high power laser experiments, and to train the next generation of scientists for laser-based research and applications. Users who submit proposals through an annual call are selected by an external and independent review panel not involving personnel from any of the facilities and managed by DOE. The broad range of capabilities of the various facilities and the open mission of LaserNetUS puts it in an excellent position to significantly contribute to an enhanced effort to develop science, technology and workforce for inertial fusion energy (IFE).

LaserNetUS can serve as a platform for users to study laser-target energy coupling, test unique target designs, develop new capabilities in targetry, materials development and testing, diagnostic development, driver technology, high-repetition-rate experimental capabilities, and simulations with a particular emphasis on machine learning. These capabilities can be then used to inform the design and implementation at higher energy IFE systems. Many of the LaserNetUS institutions and personnel are already directly involved in high-energy-density physics and inertial confinement fusion research highly relevant to IFE as part of their own research programs as are many of our current users. LaserNetUS is configured to adapt to changing priorities with a newly formed, but large, community of users and advisory groups to facilitate responsiveness. The 10 LaserNetUS facilities have different but overlapping and complementary capabilities, both in laser systems and experimental facilities and apparatus, that make them suited to support advances in IFE. By design, workforce development is a high-level priority of LaserNetUS and the effectiveness of LaserNetUS in this regard is already apparent. This can help address surging demand for highly trained scientists and engineers specializing in the interaction of intense light and matter.

An Introduction to LaserNetUS

LaserNetUS has already had a large impact on the high energy density physics community, completing more than 50 experiments involving over 400 users (including over 100 students), but it is a relatively new entity, so an overview is provided. LaserNetUS was established by the Department of Energy in August 2018 with seven participating high peak power laser facilities and has now grown to ten institutions geographically distributed throughout the US and Canada. It is dedicated to the proposition that there should be broad access to high power laser facilities. Such facilities are expensive and difficult to maintain, but LaserNetUS provides access to a wide range of ultrafast, untraintense laser facilities at no cost to its users. A detailed description of the facilities and laser systems can be obtained from the LaserNetUS website: https://lasernetus.org/. All of the laser facilities have multiple laser systems and/or multiple modes of operation. These include different ranges in pulse energy and repetition rate, different wavelengths, options for multiple beams active simultaneously, and more. A large number of different experimental chambers are provided with many laser and experimental diagnostics offered by the facilities. Again, a detailed list is available at the web site. Users obtain run time via a proposal submission process run by DOE and independent of the facilities. Proposals are reviewed, ranked, and allocated to facilities by a proposal review panel (PRP) of national and international experts who are anonymous to facility personnel with the exception of the PRP Chair. The first chair was Dr. Tammy Ma (LLNL), who established much of the reviewing protocols. The current chair is Dr. Ariana Gleason (SLAC). In the short time LaserNetUS has been in operation, three cycles of experiments have been completed at the time of this writing with 84 proposals awarded run time. Cycle 1 and Cycle 2 runs are complete and Cycle 3 runs are well underway, scheduled to complete later this year. The call for Cycle 4 is closed and proposals are under review. In addition to receiving run time, our users may request funding from DOE to support their runs, for example, for targets, travel, critical instrument, or facility upgrades to accommodate their experiments. Such upgrades have included addition of long focal length beamlines and betatron source development. For the first three cycles, about 58% of submitted proposals have been awarded run time with proposals received from 123 institutions involving more than 400 unique participants. We have instituted annual meetings, with the last in August, 2021.



Overview of LaserNetUS proposal submissions and awards, participants, applicant institutions

The LaserNetUS Community. LaserNetUS represents a large swathe of the high-power laser community with many directly involved in HEDP and ICF and many others who would be interested in joining the new IFE effort. LaserNetUS is governed by the facility PIs/POCs (see Cover page) who elect a Chair and Vice-Chair , Dr. Felicie Albert (LLNL) and Dr. Douglass Schumacher (OSU) respectively, and who are advised and guided by DOE through the FES program manager, Dr. Kramer Akli, and our Program Coordinator, Chandra Curry. All meet regularly, typically weekly. Regular guidance is provided by the PRP Chair, Dr. Arianna Gleason, as well. However, a broader LaserNetUS Community has grown consisting of many scientists who contribute their time to the LaserNetUS effort. This has considerable significance for LaserNetUS's future contribution to IFE. We are advised by a Scientific Advisory Board led by Dr. Roger Falcone (UC Berkeley) with 12 members (including 2018 Nobel Prize winner, Dr. Donna Strickland (U. Waterloo)). We have a large and growing User Group led by Dr. Ronnie Shepherd (LLNL) and Dr. Amina Hussein (U. Alberta) that advises LaserNetUS on current needs and future directions. We are working with our users to develop new diagnostics and to establish common diagnostics in an effort led by the Common Diagnostics and Data Committee (Chaired by Dr. Christine Krauland (General Atomics) and co-Chaired by Dr. Mingsheng Wei (LLE, LaserNetUS). Finally, we are working on developing network-based support for the many kinds of simulations needed for a successful experiment with a new Simulations Group led by Dr. Scott Wilks (LLNL) and Dr. Petros Tzeferacos (U. Rochester). At the same time, a substantial outreach effort is underway to better connect with universities and the private sector in the United States as well as a range of international organizations, including LaserLab Europe and The Extreme Light Infrastructure facilities.

LaserNetUS and Development for IFE

Many of LaserNetUS personnel and institutions are already directly working on IFE-relevant HEDP and ICF research through their own research programs. Prominent examples of this include LLNL's leading work on the Indirect-Drive ICF which has achieved a burning plasma recently on the National Ignition Facility [1], LLE's leading work on the development of Direct Drive ICF and advanced drivers, and the LCLS MEC's work on measuring equations of state, and advanced diagnostic and driver work at LBNL and elsewhere. LaserNetUS is well poised to advance IFE by facilitating user access to laser-based experiments as our users anticipate and address challenges in the long-term development of IFE. LaserNetUS will adapt and potentially expand to better facilitate the new experiments including the exploration of IFE target physics requested by our users. Our organization, described above, and our relationship with DOE is specifically geared for this kind of flexibility. We have identified multiple areas where we are likely to be able to advance the field. This white paper describes opportunities to facilitate our users in the HEDP and IFE communities.

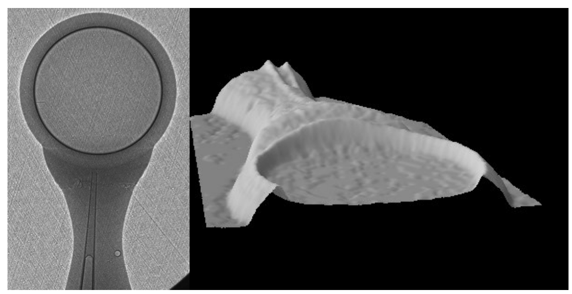
Target Developments

Although extraordinary advances in targetry design and metrology facilitated the recent demonstration of a 1.3 MJ yield at LLNL, orders of magnitude increase in repetition rate and decrease in cost are required. This is an extraordinary challenge. Since its inception, LaserNetUS has focused on high repetition rate target design to facilitate use of the many high repetition rate modes available to our users (up to 1 Hz, 10 Hz, and 1 kHz, depending on the pulse energy) with several of our lasers providing PW pulses at > 1 Hz. This requires fielding the targets with excellent alignment, verifying their condition, and addressing debris after the shot. We can support experiments designed to develop the technology to position an IFE relevant target (or aim the laser systems) and verify its integrity at high repetition rate. This will require rapid coordination of the lasers and diagnostics using closed loop systems. Substantial work in this direction is underway at LBNL, MEC, OSU, and CSU.

Materials

There are many opportunities for laser processing and characterization of materials as well as exploring material properties under extreme conditions. One such example is neutron radiography and neutron physics. LaserNetUS facilities and users are working on development of compact neutron sources, for example, at OSU and U. Texas Austin, where ion acceleration by petawatt lasers is harnessed for neutron production., CSU and LLE, and others including LBNL are working on the proton sources that underlie them. A key requirement to use laser-based neutron sources to study, for example, neutron mediated damage is high yield at high repetition rate. A successful system will have substantial advantages over traditional neutron sources in high peak flux, ease of use, cost, and safety. Newly developed laser technologies have overcome the repetition rate limit for the laser drivers, but not yet for neutron generation. The entire laser-target/converter-diagnostic apparatus must operate robustly at high repetition rate for an extended time. Two of only a few petawatt-class lasers operating worldwide at repetition rates equal to or greater than 1 Hz, are part of LaserNetUS. Network members have developed new technologies for high repetition rate targets, and rapid diagnostics. By combining the expertise of the different facilities, technical hurdles can be overcome. Several users have already been awarded multiple runs (via sequential proposal calls) at different facilities, effectively allowing different facilities to work in concert, each with their own complementary strengths. The higher repetition rate, multi-hundred Joule lasers being developed within LaserNetUS facilities will make possible high average flux neutron beams and will open new avenues for fusion materials studies.

Diagnostic Development and fundamental target physics



Phase contrast image of a spherical capsule (2mm diameter) and phase reconstruction (reference [4]).

Diagnostics such as X-ray backlighting (including betatron beams) are key tools for a sustained effort devoted to the improved understanding and control of target physics in an IFE program. The ALLS facility has developed and improved a betatron beam line over the years, based on ultrafast laser wakefield acceleration (LWFA) [2], operating in the few-keV to 50keV range. This X-ray source is complementary to other backlighting sources developed at other LaserNetUS laboratories such as CSU, MEC, LLE, LLNL, LBNL, and U. Nebraska. The ALLS betatron X-ray source has been tested in two directions of interest for an IFE program, which are phase contrast imaging and X-ray absorption spectroscopy, and is now operated at a 2.5Hz repetition rate. Phase contrast X-ray imaging [3] enables a real-time examination of the ICF laser driver interaction with the target, especially during the acceleration phase of the imploding shell where deleterious hydrodynamical instabilities can take place. We have demonstrated that a laser-based synchrotron X-ray source could be used to image and characterize in a single laser shot spherical capsules similar to ICF targets with a 4.3 μm spatial resolution in the object plane [4]. This is an example of the many advanced diagnostics available through LaserNetUS. Others include quasi-monoenergetic MeV photon sources at UNL and LBNL that could provide micron-scale resolution of compressed IFE cores. Proton acceleration (noted above, under development by users at many facilities) can provide both density and field probes. In the longer term, there is potential for compact free electron lasers. These methods are being driven by mid scale lasers that in the near term are available under LaserNetUS and in the longer term are small enough in scale to be integrated into IFE research facilities/drivers.

LaserNetUS also offers many platforms for scaled studies of fundamental target physics for IFE. An experiment by University of Michigan and collaborators demonstrated micron-scale resolution of fundamental hydrodynamic instabilities using both betatron photons (measuring density) and electrons (measuring field) at LBNL. The high resolution combined with 1 Hz-class rate is an example of the unprecedented precision LaserNetUS can offer to the fundamental physics underlying IFE. Another experiment by UC San Diego (PI: J. Kim) and collaborators from LLNL explored a new approach to ion acceleration by continuous fields in target transparency regime with multi-ps pulses using the high-energy OMEGA EP laser that have demonstrated the maximum proton energy > 70 MeV and significantly higher yield of protons in higher energy than expected from a typical target-normal-sheath-acceleration mechanism. Laser-driven intense ion beams are particularly appealing to HEDP and IFE for its potential broad range of applications that include novel laser fusion schemes, namely proton fast ignition, neutron sources and, a powerful particle probe tool for IFE.

Simulations

Simulations, including empirically based ones, have been critical for the development of HEDP and ICF, including the recent 1.3 MJ shot at LLNL. In the future, additional modes of operation will be required as well as those in use. Machine learning (ML) tools may greatly facilitate the development of practical IFE, including target and laser handling and operations. These tools may have to operate in an environment where the large data sets typically used for ML are not available, despite repetition rates that are considered high for HEDP and IFE (ie. 1 Hz). The LaserNetUS Simulation Group, described above, already includes experts in hydrodynamic and kinetic modeling approaches, hybrid modeling approaches, synthetic diagnostics, and more. To experimentally constrain these models and inform IFE physics, LaserNetUS facilities can provide a range of pulse energies exceeding 100 J (LLNL, LLE, U. Texas) with multiple shots per day or, at much lower energies, exceeding 1 Hz (LBNL, CSU, ALLS). Working in combination, these are ideal systems to develop ML tools for control of targets and lasers and for rapid analysis if diagnostics that can then be tested at the highest energies and repetition rates required for IFE.

Workforce

With Cycle 4 getting underway, the number of participants in LaserNetUS will exceed 400 scientists in the short time that LaserNetUS has been in operation (just over 3 years). Many of these users are involved in HEDP and ICF, but many are performing basic plasma research, sometimes involving intense magnetic fields, working on extreme-pressure phenomena, investigating physics at the ultra-fast scale, or exploring high-energy particle physics. This latter group of users represents a pool of talent that could be tapped to address the substantial challenges mentioned above. Advancing the careers of young scientists is a <u>primary</u> emphasis of LaserNetUS, focusing on <u>all</u> aspects of career development. In the first three cycles, we had 17 undergraduate and 116 graduate student participants (unique participants, not counting multiple runs by the same student) and 49 postdoctoral researchers; 46% of our participants were early career. Many of the proposals had graduate students or postdoctoral researchers as PI or experimental lead. These have resulted in successful experiments which results have been published in leading journals such as Nature Physics and Physical Review Letters. Groups are encouraged to have young career scientists as their spokespeople, if appropriate, and many post-docs were. At our recent annual meeting in 2021, many groups chose to have graduate students summarize their current findings in the invited talks. These young scientists obtain hands-on training at our state-of-the-art facilities and get to experience the excitement of research in HEDP. They are ideal candidates for recruitment into future IFE programs.

Conclusion

LaserNetUS can serve as a unique, cost effective platform for the development of many of the necessary technologies required for IFE in support of efforts at national labs and private industry. LaserNetUS is already configured to help large numbers of users obtain access to the brightest light and to develop novel experimental approaches for many aspects of IFE. Particular emphasis include advanced diagnostics, material science, fundamental hydrodynamics, and laser-plasma interactions. A LaserNetUS community has formed, bringing together different groups to work on problems of common interest. Work on HEDP is already part of the mission of LaserNetUS through its users. Advances in this area will also necessarily help develop the workforce needed to support a new program in IFE.

References

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